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SWITCHING SYSTEM FOR THE FXR ACCELERATOR

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Summary

A switching system has been designed for a 20 MeV flash x-ray linear induction accelerator which is being built at Lawrence Livermore Laboratory. The switching system fans out a single command pulse and amplifies it to obtain the voltage necessary for reliable, low-jitter triggering of the accelerator components. This system consists of two major subsystems: (1) the Blumlein Charging Subsystem which first triggers thirteen Marx generators, and then charges 54 water-filled Blumleins, and (2) the Blumlein Triggering Subsystem which triggers the already-charged Blumleins to produce a 90 nanosecond, 400 kV pulse in each of 54 ferrite-loaded accelerator modules. The first subsystem consists of charged high voltage cabling with two parallel switch gaps either of which will trigger the Marx generators. The major components of the second subsystem are three stages of switch gaps along with the necessary high voltage cabling. Two parallel first stage switch gaps trigger thirteen second stage gaps, which in turn trigger 54 third stage Blumlein switch gaps synchronous with the passage of the electron beam pulse. These spark gaps are operated at a voltage of 150 to 350 kV with a 1/3 hertz repetition rate. Varying the cable lengths creates the actual delay times in the triggering of each component. Redundancy is built into the system to insure the high reliability which is essential for the flash radiography application.

Introduction

Flash X-Ray (FXR) is a 20 Mev, 2 KA linear induction accelerator composed of 54 accelerating cavities. Six of these cavities make up a 1.5 MeV electron injector and the remaining 48 cavities, arranged in four module sections, each accelerate the electron beam 380 kV. The accelerator has an overall length of 39 meters. FXR uses thirteen Marx generators for energy storage and 54 water-filled Blumleins as pulse-forming networks to supply a 90 ns, 380 kV pulse to each of the 54 ferrite loaded accelerating cavities. The operating sequence is as follows. Each of the Marx generators charges up 4 cavity Blumleins. When the Blumleins are at peak charge they are triggered and send a 90 ns 300 kV pulse to the accelerating cavities. A mismatch between the Blumlein and cavity results in a 90 ns 380 kV pulse across each of the cavity gaps resulting in an overall beam energy of 20 MeV.

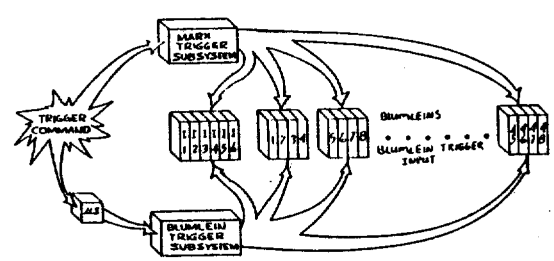
An overview of the FXR accelerator is given by B. Kulke[1] and specifics are given by G. E. Vogtlin and R. W. Kuenning[2] and H. B. MacFarlane and R. Kihara[3] at this conference. This paper will deal with the means by which each of the accelerator components are triggered.

The purpose of the Switching System is to first charge and then trigger each accelerator Blumlein to produce the accelerating voltage across each accelerator module gap coincident with the passing of the electron beam. Since this machine will be used for radiography shots, which are expensive one-time shots, it is essential that the accelerator be very reliable. Therefore the Switching System itself must have a high reliablility.

The predicted lifetime of this accelerator is about twenty years. Over this time the accelerator will have fired several million shots. (Most of these shots will be for machine tuning and hardware checking, and a small percentage will actually be radiography shots). Therefore it is necessary for the Switching System to have a long lifetime (approximately millions of shots) with very little down-time for periodic maintenance and repairs. Another requirement is that the system readily accept machine upgrades, since at present machine upgrades are expected which would increase the beam energy from 20 MeV to as much as 50 MeV.

The Switching System is composed of two major subsystems, the Blumlein Charging and the Blumlein Triggering Subsystems. The first triggers the Marx generators which in turn charge the accelerator Blumleins, and the second triggers these already charged Blumleins (Fig. 1).

THE MARX TRIGGER SUBSYSTEM CAUSES THE ACCELERATOR BLUMLEINS TO CHARGE, WHILE



THE BLUMLEIN TRIGGER SUBSYSTEM TRIGGERS THE ALREADY CHARGED ACCELERATOR BLUMLEINS

FIGURE 1

The Blumlein Trigger Subsystem

As stated earlier, the purpose of this subsystem is to trigger each of the accelerator Blumleins at the proper time to obtain optimum acceleration of the electron beam. Optimum

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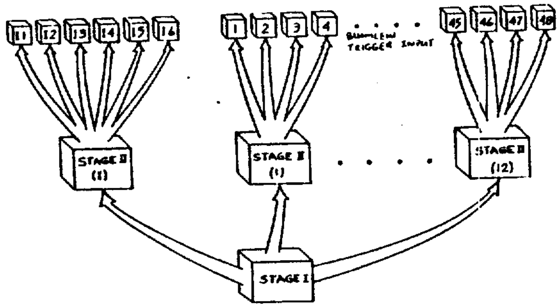
acceleration creates a beam of maximum energy with minimum energy spread.

The Trigger Subsystem can be broken down into three levels or stages. The purpose of each stage is to amplify the trigger signal of the previous stage. Initially a single one kilovolt trigger signal is fed into the first stage. This stage amplifies the signal into thirteen 125 kV trigger pulses. These thirteen trigger pulses enter the second stage and are further amplified to fifty-four 150 kV trigger pulses. The signals then go on to trigger each of the fifty-four Blumleins (Fig. 2).

THE BLUMLEIN TRIGGER SUBSYSTEM CAN BE BROKEN UP INTO THREE LEVELS OR STAGES.



EACH STAGE OF THE BLUMLEIN TRIGGER SUBSYSTEM FANS OUT TO THE NEXT STAGE

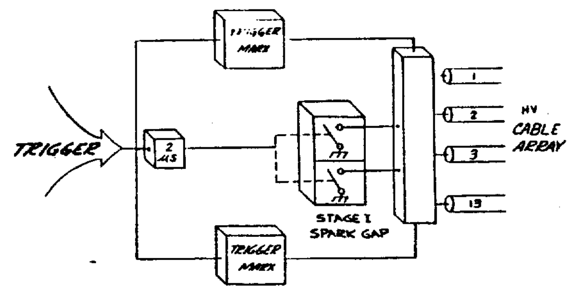
FIGURE 2

a. Stage 1

The block diagram of the first stage of the Trigger Subsystem is shown in Fig. 3. The first stage consists of an array of 13 High Voltage Cables, two spark gaps, and the output from two Marx generators, all connected at a common point. These two Marx generators, or trigger Marxes, are two-stage, 250 nf devices. They are modified versions of the thirteen Marx generators which charge the accelerator Blumleins. Each of these thirteen Marxes is a five stage, 75 kV per stage, 100 nf Marx generator. The trigger Marx is a single five stage Marx split into two two-stage trigger Marxes, (one complete stage is dropped), each having its own charging and triggering circuit. The capacitors, spark gaps, and remaining circuit elements of the trigger Marxes are identical to those of the five stage Marxes, minimizing the number of on-hand spare parts needed. The trigger Marx charging supply is also identical to the charging supplies of the accelerator Marxes.

The spark gaps for this first stage are identical to the spark gaps that will be used to trigger the accelerator Blumleins. The spark gap electrodes are coaxial with the trigger electrode located midway between and concentric with the two main electrodes. Past testing has shown that this type of gap has an inductance of about 60 nanohenrys. H. B. McFarlane[3] has completed a set of experiments in the gap which show it has low no-fire, pre-fire characteristics and has an RMS jitter of less than 1 ns when operated with SF_6 at voltages of 325 kV. Since the spark gaps on the switching system will

THE TRIGGER MARXES ARE ERECTED AND CHARGE THE THIRTEEN TRIGGER CABLES



REDUNDANT MARXES BETTER INSURE THAT THE CABLE ARRAY IS CHARGED

FIGURE 3

be operated at 125 kV, further testing at this lower voltage is necessary.

A -120 kV pulse with a 10-90% rise time of 10 ns or less will trigger these spark gaps. This pulse will be generated by a four stage 4.2 nf Marx. A three-stage version of this Marx has had extensive use at the Lawrence Berkeley Laboratory Electron Ring Accelerator[4]. There it has proven itself to be highly reliable with a tested lifetime of over 10 million shots. The only design change we will make will be adding another stage, making it a four stage -30 kV/stage unit.

The cable array will be high voltage cable rated at 350 kV dc. This cable has a characteristic impedance of 67.6Ω, a capacitance of 23 pf/ft and a phase velocity of .63 times the speed of light in vacuum.

The cable array consists of thirteen cables varying in length from 30.2 to 48.2 meters. The difference in length between each of the thirteen cables corresponds to the electron transit time between the adjacent four cavity sections (Fig. 4).

THE TIME IT TAKES FOR THE TRIGGER PULSE TO REACH EACH STAGE II GAP IS DEPENDENT UPON THE LENGTH OF EACH TRIGGER CABLE.
THE DIFFERENCE IN LENGTH BETWEEN EACH CABLE CORRESPONDS TO THE ELECTRON TRANSIT TIME BETWEEN EACH SECTION.

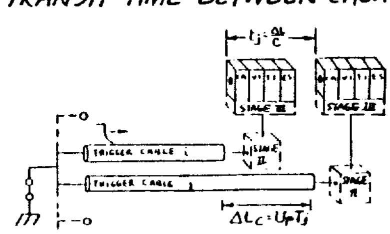


FIGURE 4

The junction where the trigger cables, trigger Marxes and Stage I gaps come together is called the fanout assembly. The trigger cables plug into ceramic damping resistors which are attached to the center conductor of the fanout assembly. The fanout assembly is shown in Fig. 5 and is 71 cm. long by 19 cm wide by 20 cm deep. The cables are arranged in two rows of eight. (The three extra connectors are for minor upgrades to the accelerator.) The two coaxial spark gaps are arranged on either side of the fanout housing while the output from the trigger Marxes enter from the bottom. This entire assembly is mounted on top of an oil filled tank containing the trigger Marxes, charging inductor along with the rest of the Stage 1 hardware.

STAGE 1 FANOUT ASSEMBLY

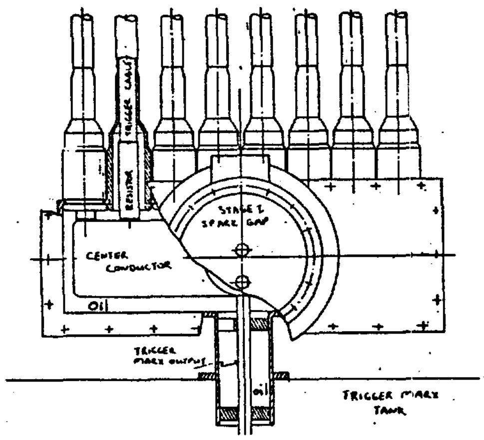


FIGURE 5

When the Marx generators are triggered, they resonant-charge the cable array to 125 kV in 2 microseconds. At peak charge, the two spark gaps are triggered, shorting the cable array to ground, and setting up a -125 kV traveling wave in each of the 13 cables. Each of these cables is terminated in a 100 pf isolation capacitor. Since these capacitors are much smaller than the cable capacitance, the -125 kV trigger pulse effectively sees an open circuit and is almost enirely reflected. The forward traveling wave combined with the reflected wave results in a >125 kV pulse which is used in the second stage of the Trigger Subsystem. In order to minimize the ringing in the cable array, 15 ohm resistors will be placed in series with each of the cables. This design was modeled by computer simulation and the resulting waveform is shown in Fig. 6. Notice that there is an acceptable voltage reversal on the cable. It is believed that this will result in an increase in the average cable's lifetime. The unwanted effect of this series resistor is that it drops the amplitude of the trigger pulse by $Z_0/(Z_0 + r)$, where r is the resistor and Z_0 is the line impedence. For the present case the trigger pulse is dropped to 0.82 of its initial amplitude. These inline resistors will be ceramic, 6 inches long and 1 inch in diameter.

In order to resonant charge the cable array in 2 microseconds, a 15 microhenry inductor will be placed in series with the Marx and cable array. The Marx itself has an inductance of about 2μh. The cable array contains 1683 feet of cable at 22.8

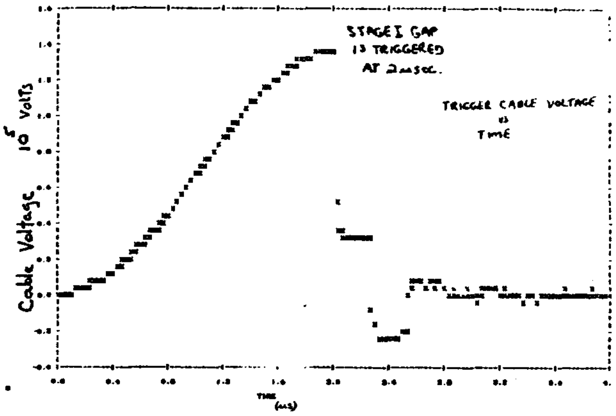


FIGURE 6

pf/ft corresponding to a total capacitance of 38.4 nf. Since the electron transit time in the largest cable (48.2 m) is much shorter than the 2μs charging time, the cable array can be treated as a single capacitor of 38.4 nf. Therefore the cable charging circuit can be represented simply by a Marx capacitance, a charging inductor, and a lumped cable capacitance as shown in Fig. 7. This figure represents the two possible conditions: first, if only a single Marx erected and second, if both Marxes erected. The voltage gain on the trigger cable is given by:

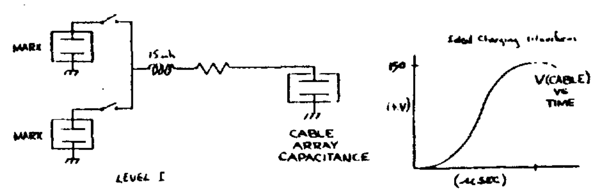
$$\frac{2C_m}{C_m + C_c} \tag{1}$$

where C_m is the Marx capacitance and C_c is the cable capacitance. The charging time, t_c, of the cable is given by

$$t_c = \pi\sqrt{LC} \tag{2}$$

where L is the equivalent charging inductance and C is the equivalent circuit capacitance. The actual voltage gain and cable charging time will depend on whether one or both of the Marx generators erect.

THE THIRTEEN TRIGGER CABLES ARE RESONANT CHARGED TO 150 KV IN ~2 μsec.



(SINCE THE CHARGING TIME IS LONG, THE TRIGGERING CABLES CHARGE AS CAPACITORS)

FIGURE 7

The reason for redundant trigger Marxes is to ensure that the cable array will be charged. If the cable array is not charged then the entire accelerator will not function leading to a failure of the radiograpy shot.

It can be shown that both the charging times and voltage gains are relatively insensitive to having one or both Marxes erect. (The voltage gain in the cable array varies by 6% dependent on whether one or both Marxes erect, while the charging time varies by less than 1%.)

Since the cable array is not a single capacitor, but is, instead, a set of thirteen transmission lines having round trip transit times of 320 ns to 510 ns. As a result the voltage waveform will be distorted from the ideal (1-cos ωt) waveform characteristic of a resonant-charge because of voltage reflections at the cable ends. In order to study this distortion, a computer code was used to model the real situation. A plot of the charging waveforms at the common end is shown in Fig. 8. From the plot you can see that there are only minor distortions. When the cable array is at its peak charge, the two coaxial stage I spark gaps are triggered, setting up a traveling wave though the cable array. A 16 ohm resistor is put in series with the trigger Marxes in order to critically damp the oscillations set up a a result of the stage I gaps firing. Two gaps are used in parallel operation in order to increase system reliability.

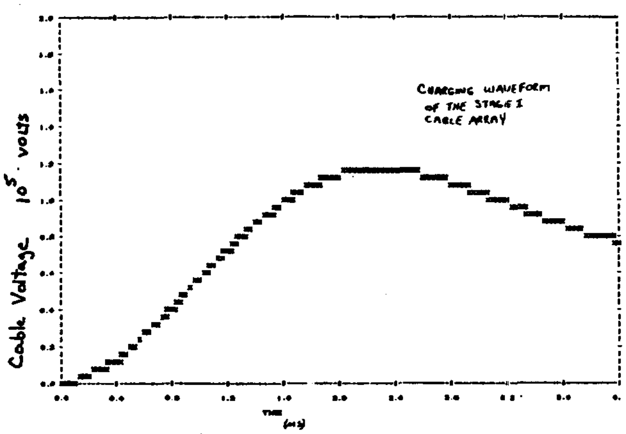


FIGURE 8

The switching system is designed to function properly if either of these gaps trigger.

b. <u>Stage II</u>

The diagram for the second stage of the Trigger Subsystem is shown in Fig. 9. This stage consists of thirteen spark gaps. A set of four trigger cables are attached to each of 12 of the stage II gaps. Each of these cables is terminated in the trigger circuit of the Blumlein stage III spark gaps. A set of six trigger cables is attached to the thirteenth spark gap and is used to trigger the Blumlein spark gaps on the six injector Blumleins. The stage II gaps and the associated trigger cabling will be charged from a tap-off from the accelerator Marxes which charge the Blumleins. Therefore, the trigger cables leading to the stage III gaps are charged to 150 kV as the Blumleins themselves are being charged to 300 kV. The trigger electrodes of the stage II gaps are located at the midplane and will be charged to 75 kV. A capacitor is needed in the trigger circuit to isolate the trigger electrode at 75 kV from the stage I trigger cable at 125 kV. This capacitor will be 100 pf or roughly 10 times the capacitance of the trigger electrode and either main electrode of the stage II gaps. A trigger pulse from the stage I cable triggers the stage II gap, shorting the stage II cables to ground and setting up a -150 kV traveling wave in the cable. The wave will then trigger the stage III gap and fire the Blumleins.

EACH TRIGGER CABLE IS TERMINATED IN A STAGE II SPARK GAP TRIGGER CIRCUIT.

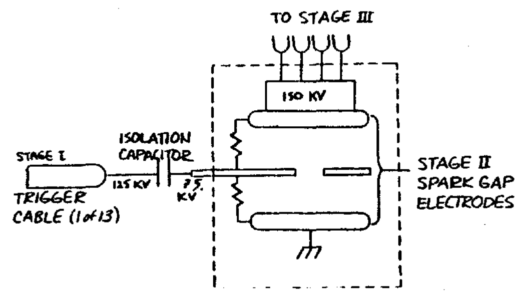


FIGURE 9

c. <u>Stage III</u>

This stage is made up of the 54 Blumlein spark gaps. The Stage II trigger cables are connected to the trigger electrodes of the gaps through a resistor. The purpose of this resistor is to minimize cable ringing in the Stage III triggering cable.

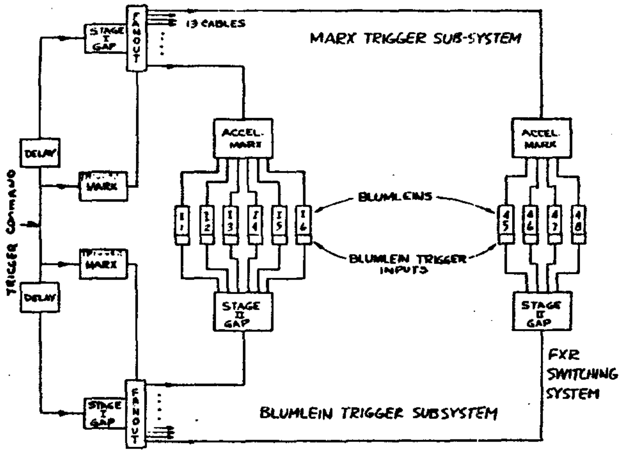
<u>Order of Firing</u>

Varying the cable lengths to each gap determines the timing of the triggering of each Blumlein spark gap. After the stage I gap is fired, the trigger pulse reaches each of the stage II gaps at the appropriate time dependent upon the cable length and sends negative trigger pulse to each of the 54 Blumlein stage III gaps. These trigger pulses reach each stage III gaps at different times again dependent on the length of each of the stage III trigger cables.

<u>The Blumlein Charging Subsystem</u>

The purpose of the Blumlein Charging Subsystem is to trigger the thirteen accelerator Marxes so that each accelerator Blumlein is at its peak charge coincident with the time that the stage III gap is triggered. The charging subsystem is identical to the first stage of the Blumlein Trigger Subsystem. Each of the thirteen trigger cables is terminated in the trigger circuit of each of the Marx generators. Since the Marx trigger electrodes are maintained at ground potential, a 100 pf isolation capacitator is placed at the trigger cable termination.

The overall Switching System is shown in Fig. 10.



OVERALL TRIGGER SYSTEM

FIGURE 10

Conclusion

The FXR accelerator must be highly reliable if it is to be a successful radiography machine. The Switching System, with its redundant systems, should prove to be very reliable. The system is easily modified for accelerator upgrades by adding similiar subsystems in parallel with the existing systems.

FXR is scheduled for completion late in 1981. The building and testing of the Switching System will begin in the next few months.

Acknowledgements

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